A new synergistic radiometer/altimeter instrument processing algorithm

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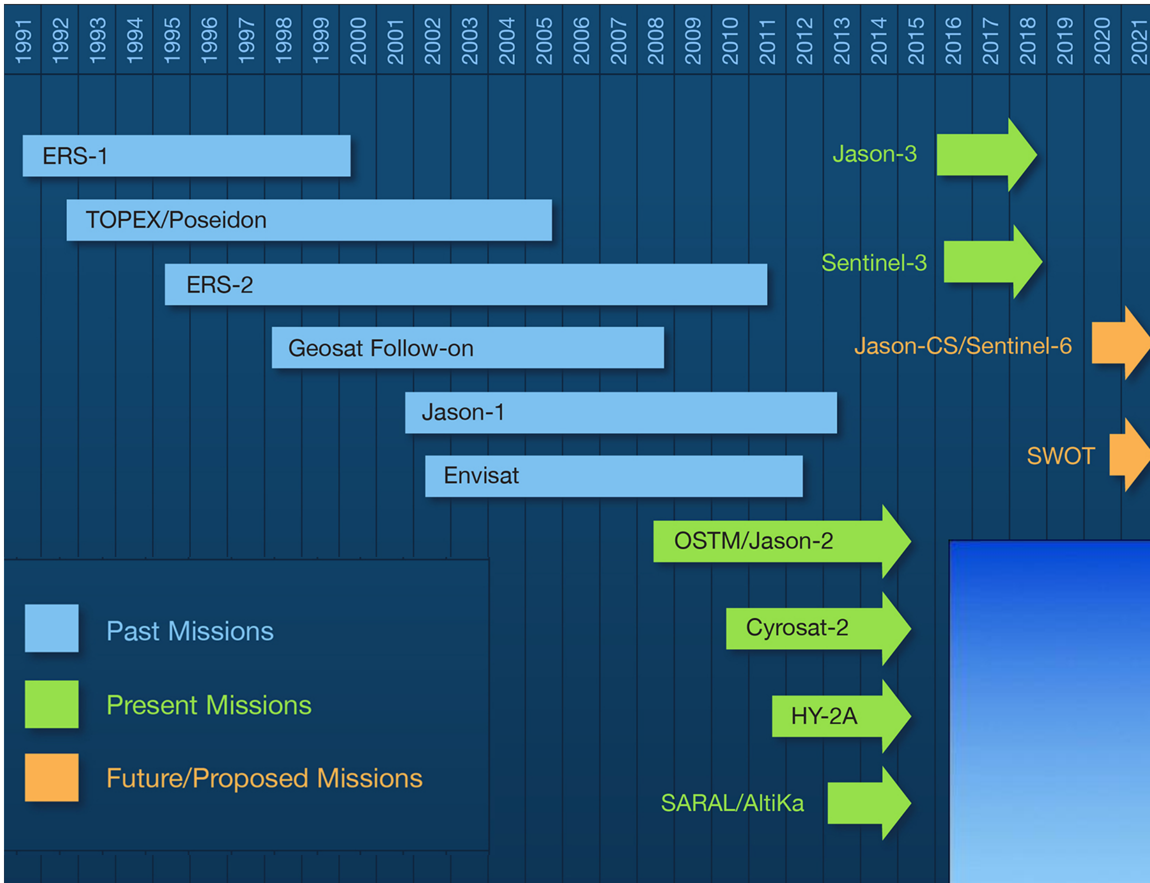
Outline

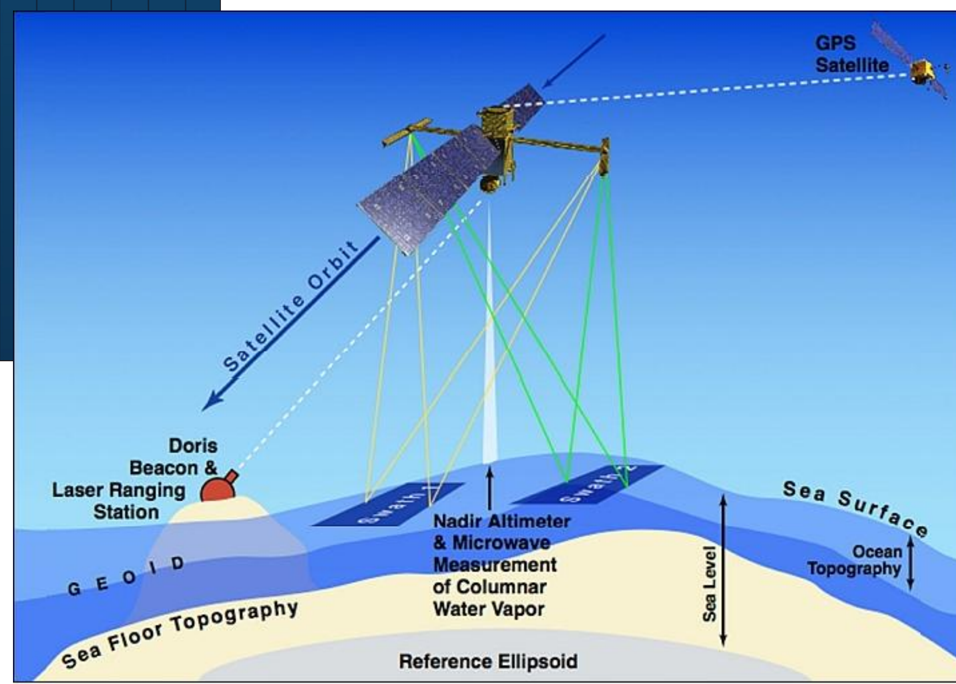
- Altimetry measurement basis
- AMR instrument and heritage algorithms
- Active/passive complementary measurements
- Combined Active Passive Retrieval System (CAPRS)
  - CAPRS: Mathematical basis
  - CAPRS: System framework
  - CAPRS: Covariance/correlation matrix
  - CAPRS: Passive microwave forward Model
  - CAPRS: Active microwave forward Model
  - CAPRS: Jacobian model and sensitivity
- CAPRS retrieval performance
- Summary and future work

Altimetry measurement basis



Source: JPL

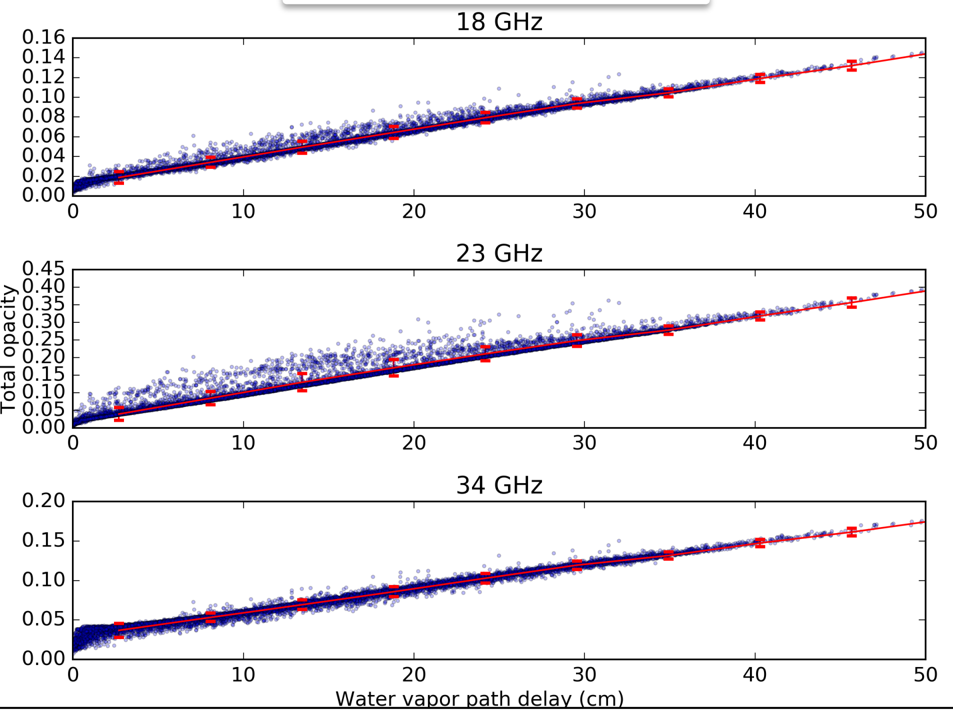
- The atmosphere reduces the speed of the radar pulse, bending its trajectory and, therefore, causing a “path delay” of the altimeter signal
- For wet tropospheric correction, passive microwave radiometers are added to the altimetry missions, e.g. AMR on Jason series.



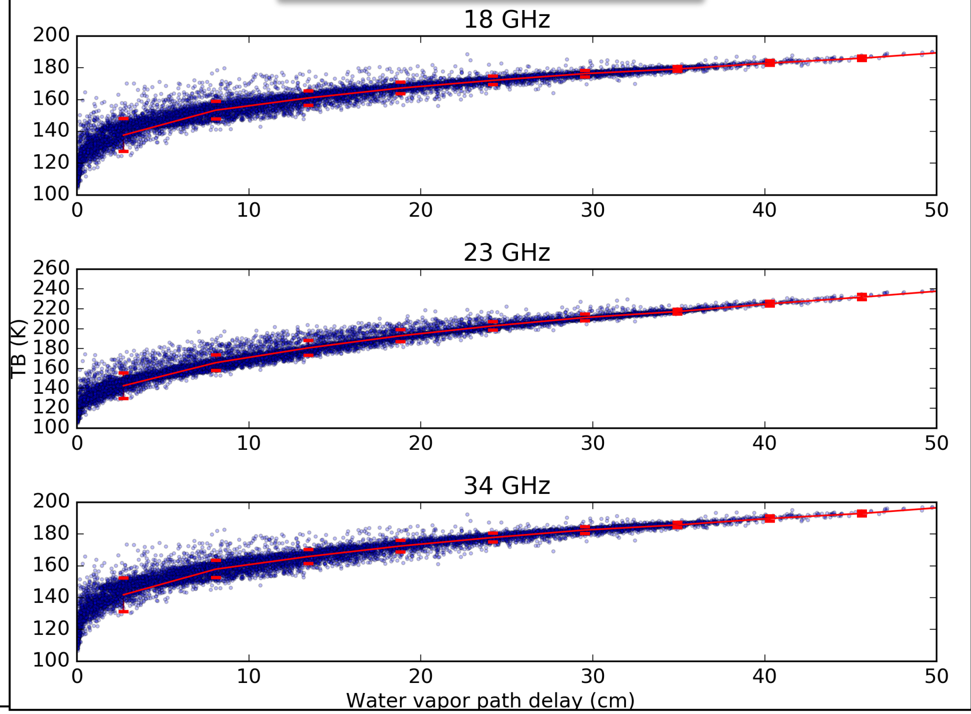
Source: NOAA

AMR Instrument Frequencies

Opacity vs Path Delay



TBs vs Path Delay



- AMR is operated at three frequencies
- Figure shows strong linear relationship between total opacity and water vapor path delay in the three AMR channels (18.7, 23.8, and 34.0 GHz). Rosenkranz absorption model is employed in this simulation.

AMR heritage algorithms

Calibrated TBs → Regression →

AMR L2 Products
Wet tropospheric correction
Wind speed
Cloud liquid water
Radiometer water vapor content
Atmospheric attenuation correction on C band backscatter coefficient
Atmospheric attenuation correction on Ku band backscatter coefficient
Rain/No rain flag
Sea ice flag

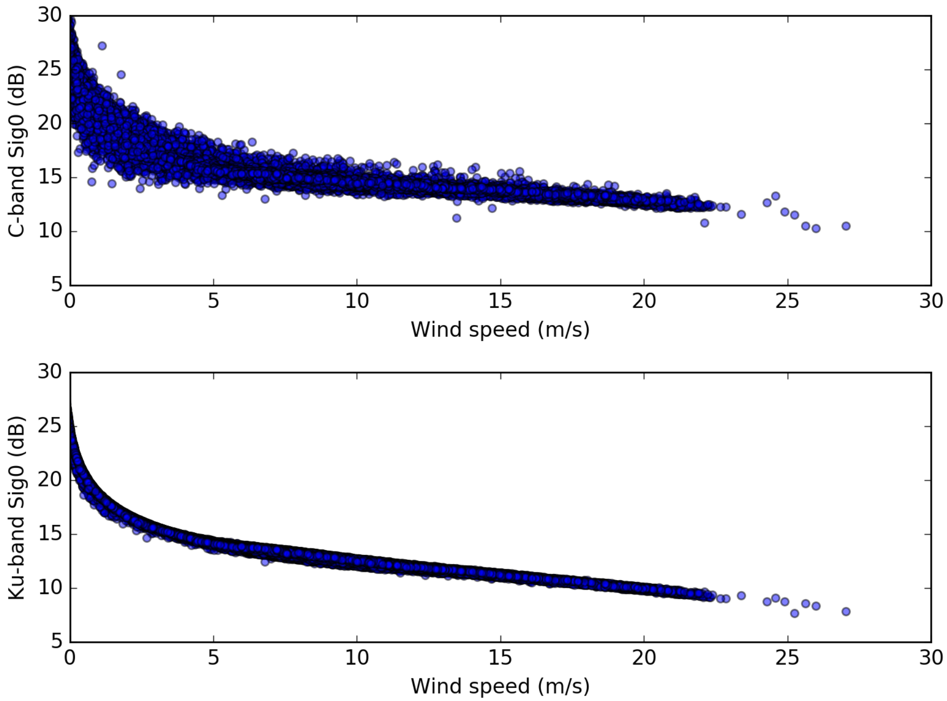
- **Limitations:**
- Altimeter and radiometer algorithms are decoupled.
- No use of altimeter backscatter signatures in the retrieval
- Multi-linear regression based, not "physically" based
- Regression algorithms are frequency dependent, thus, three frequency AMR algorithms cannot be applied to two frequency radiometers (e.g. SARAL/AltiKa, Sentinel 3)

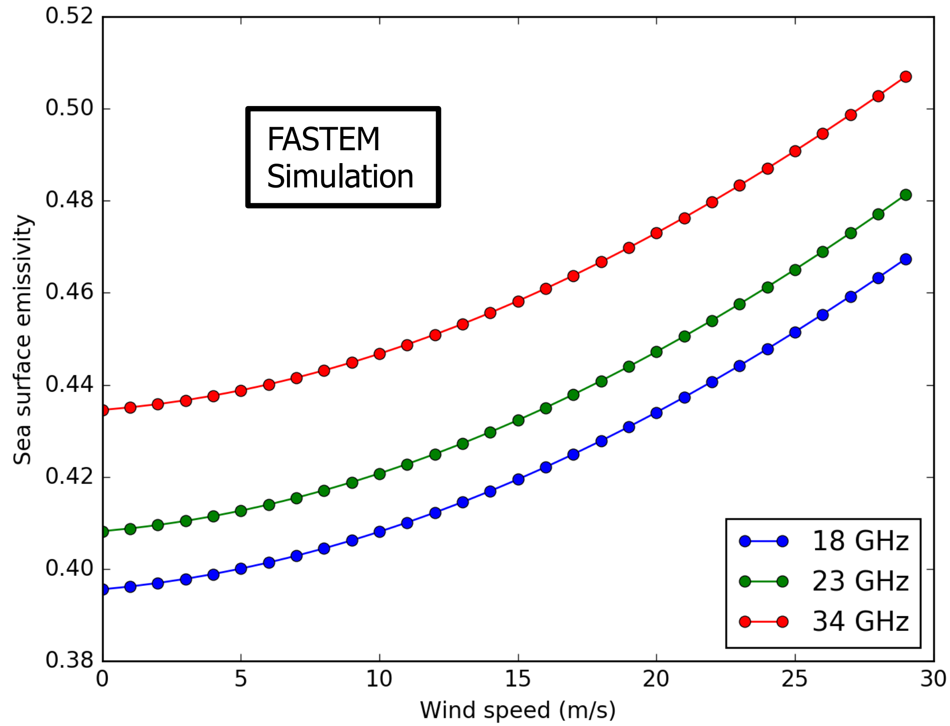
$$\mathrm{W} = \mathrm{w}_0(j) + \sum_{i=1}^{3} \mathrm{w}(f_i, j).\mathrm{T_b}(f_i) \qquad \text{(in m/s)}$$

$$\mathrm{L_Z} = \mathrm{L}_0(j) + \sum_{i=1}^{3} \mathrm{L}(f_i, j).\mathrm{T_b}(f_i) + \mathrm{L_{sq}}(j).[T_b(f_3)]^2$$

$$\mathrm{PD}^{(g)} = \mathrm{B}_0^{(g)}(j) + \sum_{i=1}^{3} \mathrm{B}^{(g)}(f_i, j)\ln[280 - \mathrm{T_b}(f_i)] \qquad \text{(in cm)}$$

Active/passive complementary measurements

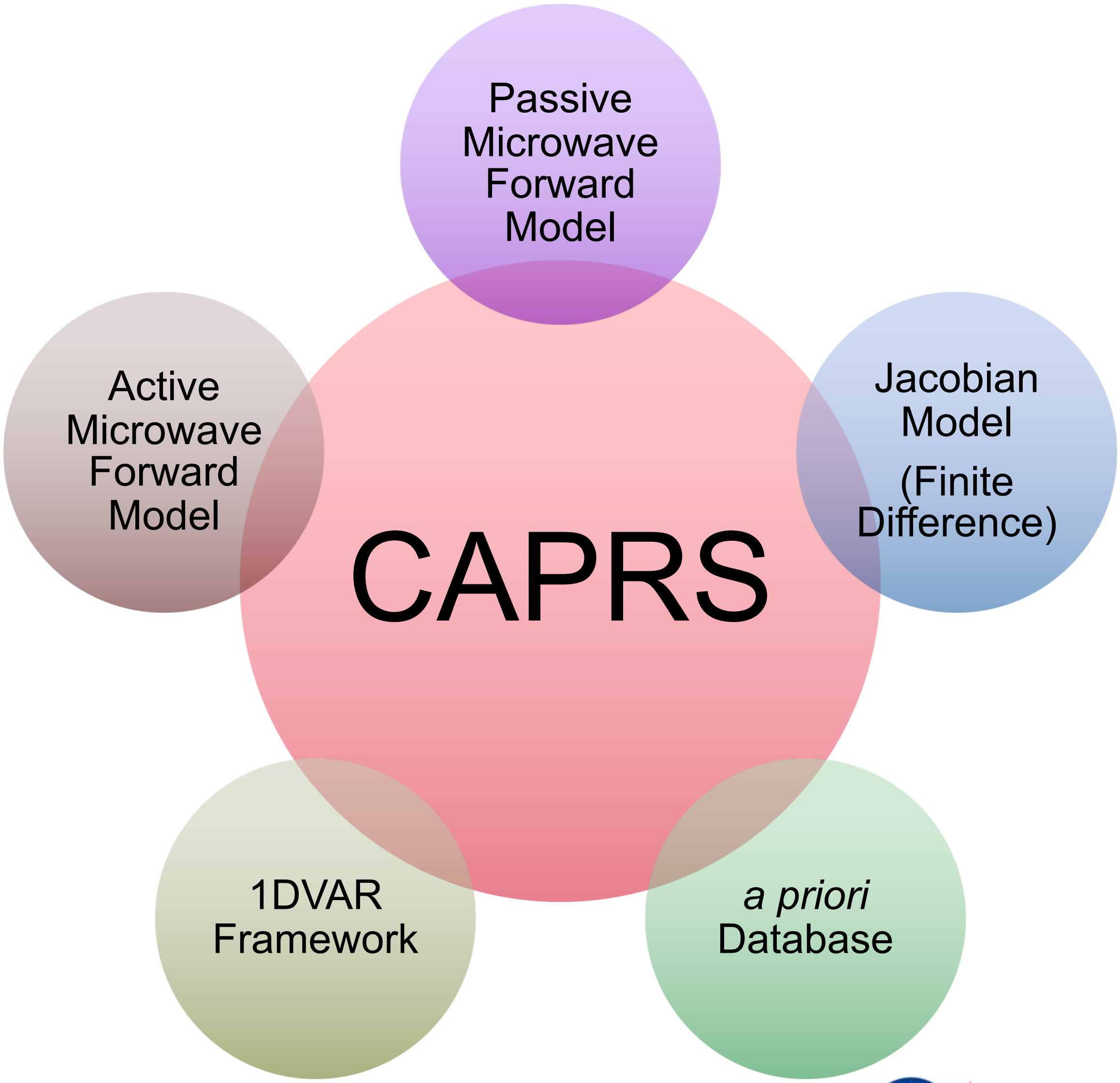




- Altimeter and radiometer measurements contain complementary information
- Therefore, a combined active/passive retrieval system should help in retrieving geophysical parameters simultaneously

Combined Active Passive Retrieval System (CAPRS)

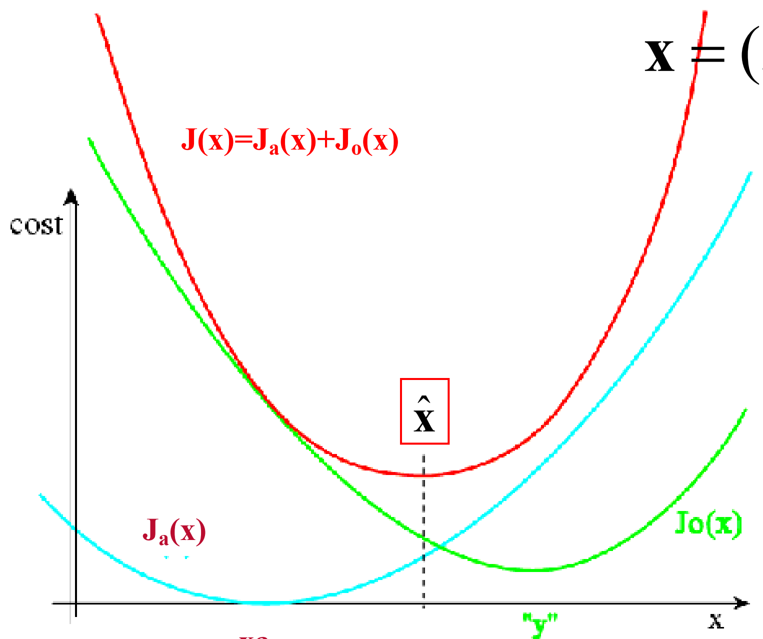
- Physically based algorithm
- Combines radiometer and altimeter information content for simultaneous retrieval of geophysical parameters
- Modular framework, can be easily extended to *any* number of radiometer and altimeter frequencies
- Open source framework in Python



CAPRS: Mathematical Basis (1DVAR)

$$J(\mathbf{x}) = \underbrace{(\mathbf{x}-\mathbf{x_a})^T \mathbf{S_a^{-1}} (\mathbf{x}-\mathbf{x_a})}_{\textit{a priori term } J_a} + \underbrace{(\mathbf{y}-\mathbf{Kx})^T \mathbf{S_y^{-1}} (\mathbf{y}-\mathbf{Kx})}_{\textit{Observation term } J_O}$$

S_a = covariance matrix of the background error
S_ε = covariance matrix of the observation error
+ covariance matrix of representativeness error (interpolation, discretization)
K = linearized forward model



Bouttier and Courtier, 1999

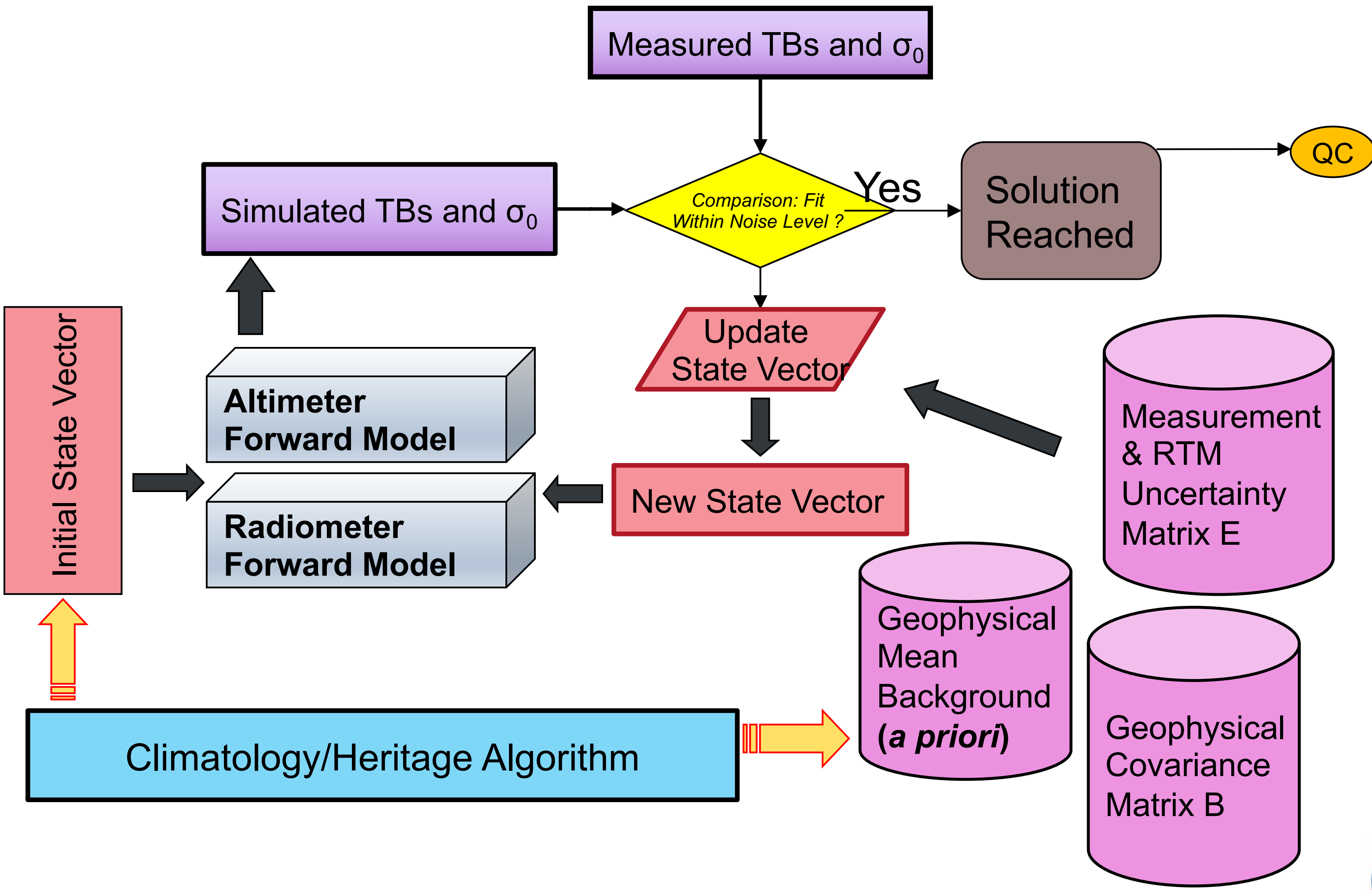
$$\mathbf{x} = (x_1, \ldots x_n)^T \qquad \mathbf{y} = (y_1, \ldots y_m)^T \qquad \mathbf{y} = \mathbf{Kx} + \boldsymbol{\varepsilon}$$

Minimization of the cost function:

$$\nabla_{\mathbf{x}} J(\mathbf{x}) = 2\mathbf{S_a^{-1}}(\mathbf{x}-\mathbf{x_a}) + 2\mathbf{K}^T\mathbf{S}_y^{-1}(\mathbf{Kx}-\mathbf{y}) = \mathbf{0}$$

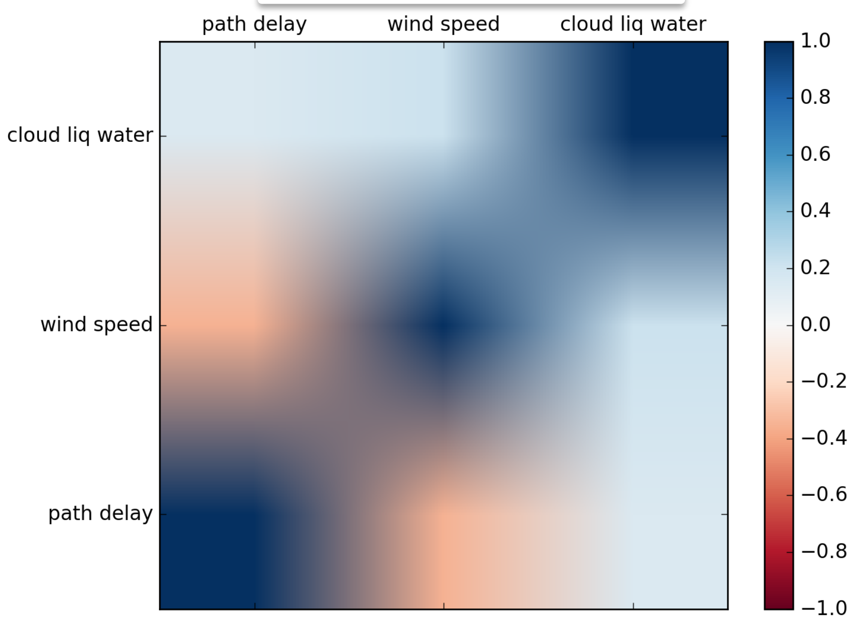
$$\mathbf{S_y} = \begin{pmatrix} \mathrm{Var}(i,i) & S_y(i,j) \\ S_y(i,j) & \mathrm{Var}(j,j) \end{pmatrix}$$

CAPRS: System Framework

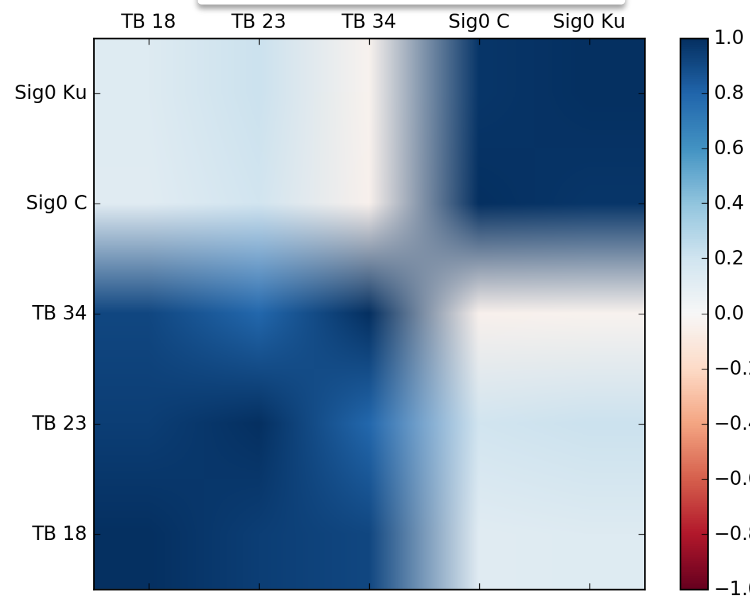


CAPRS: Covariance/Correlation Matrix

State Vector Corr Matrix



Obs Corr Matrix



$$\mathbf{x} = (x_1, \ldots x_n)^T \qquad \mathbf{y} = (y_1, \ldots y_m)^T \qquad \mathbf{y} = \mathbf{K}\mathbf{x} + \boldsymbol{\varepsilon} \text{ , where } \mathbf{K} = \frac{\partial \mathbf{y}}{\partial \mathbf{x}}$$

Jacobian Model (Finite Difference)

5 x 3

3 x 1

$$\mathbf{x} = \begin{bmatrix} PD \\ WS \\ CLW \end{bmatrix}$$

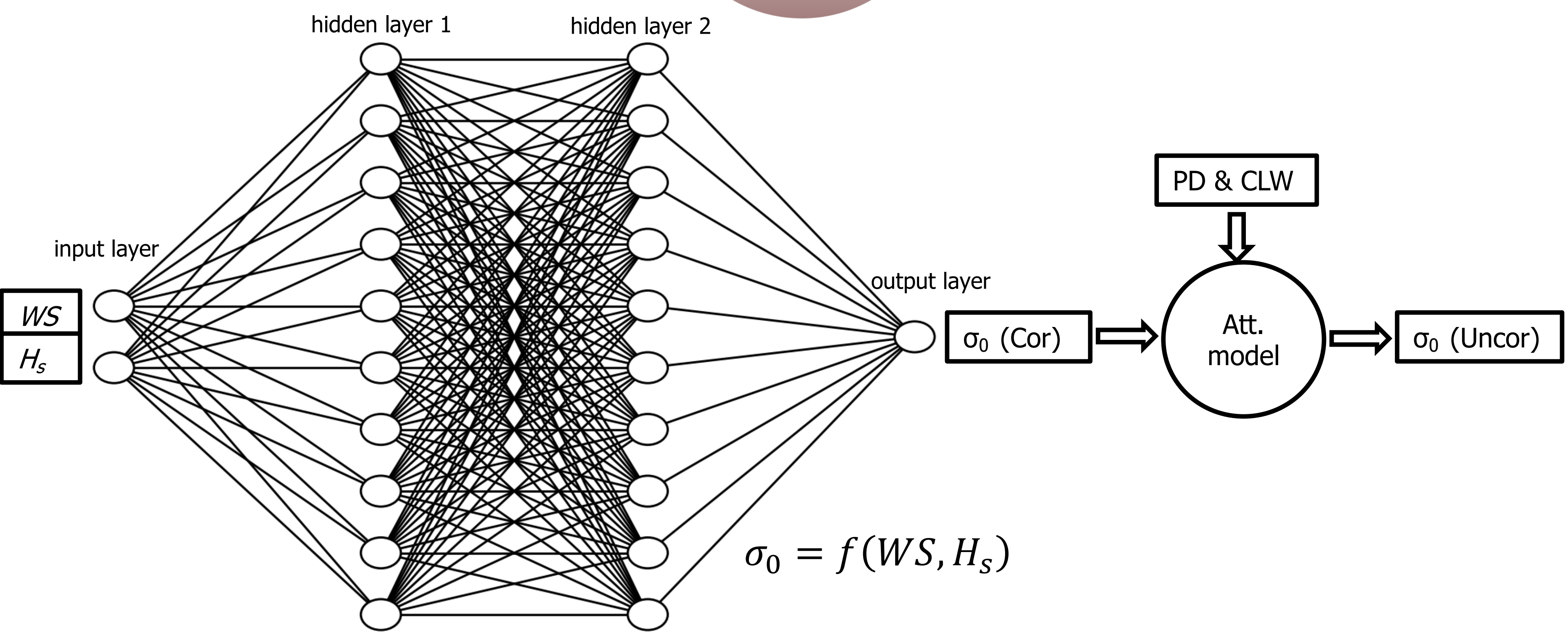
5 x 1

$$\boldsymbol{y} = \begin{bmatrix} TB18 \\ TB23 \\ TB34 \\ \sigma_0 C \\ \sigma_0 Ku \end{bmatrix}$$

A priori database is generated by combining the ECMWF model with the heritage algorithm and calibrated TBs

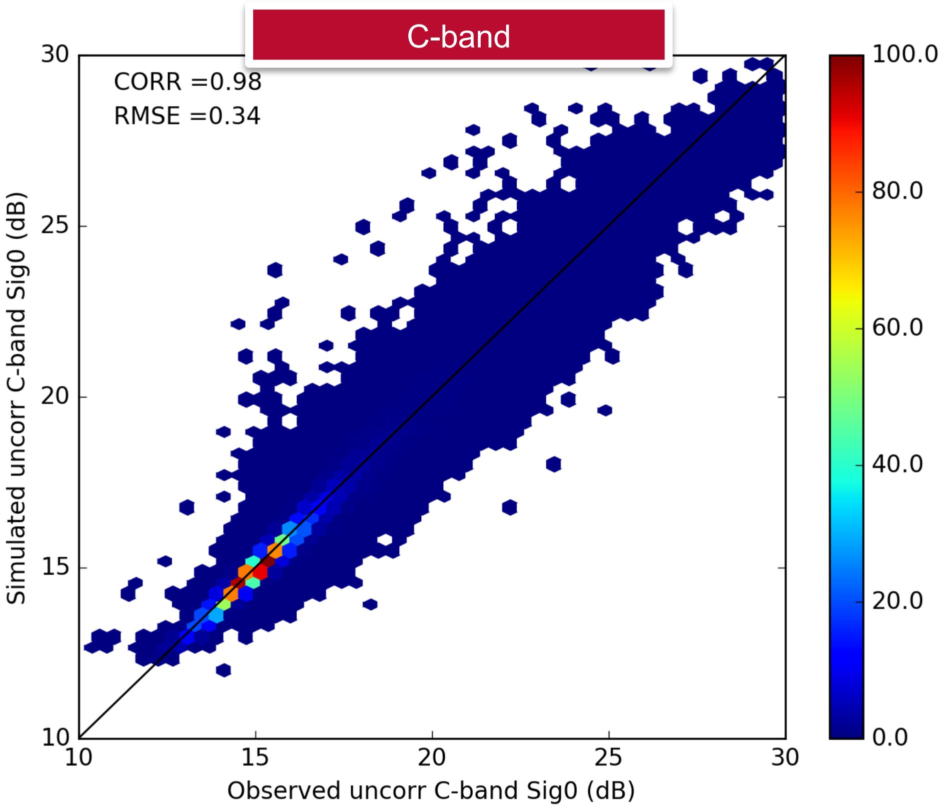
CAPRS: Active Microwave Forward Model

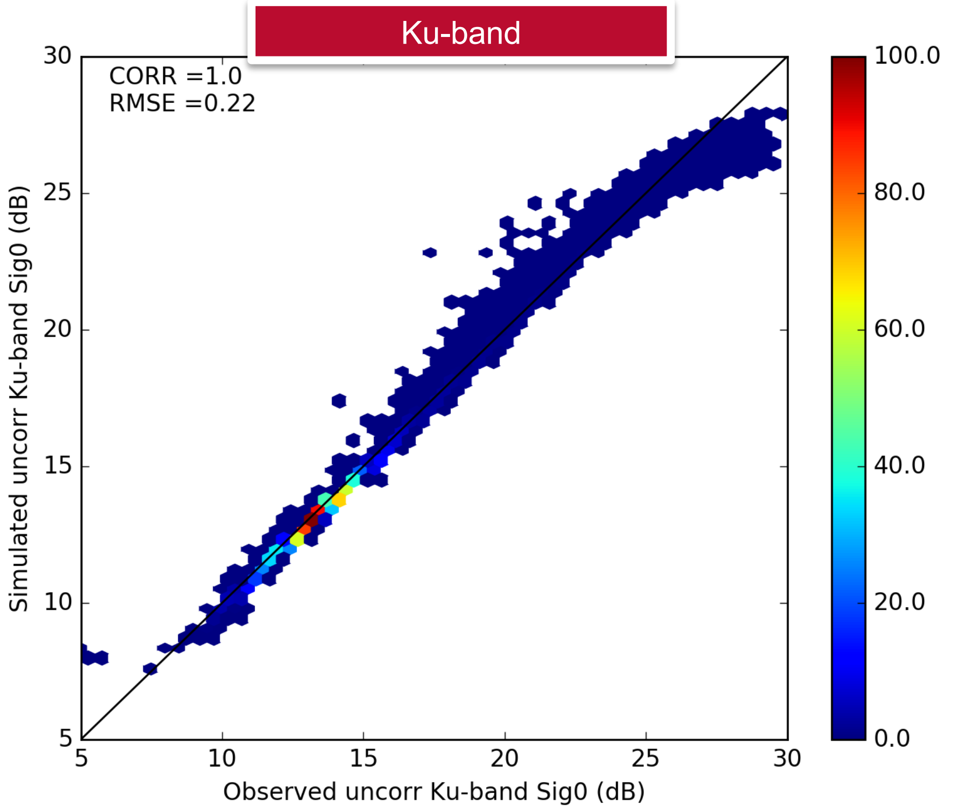
Active Microwave Forward Model



Deep neural network

CAPRS: Active Microwave Forward Model





Independently assessed using one month data (June 2017)

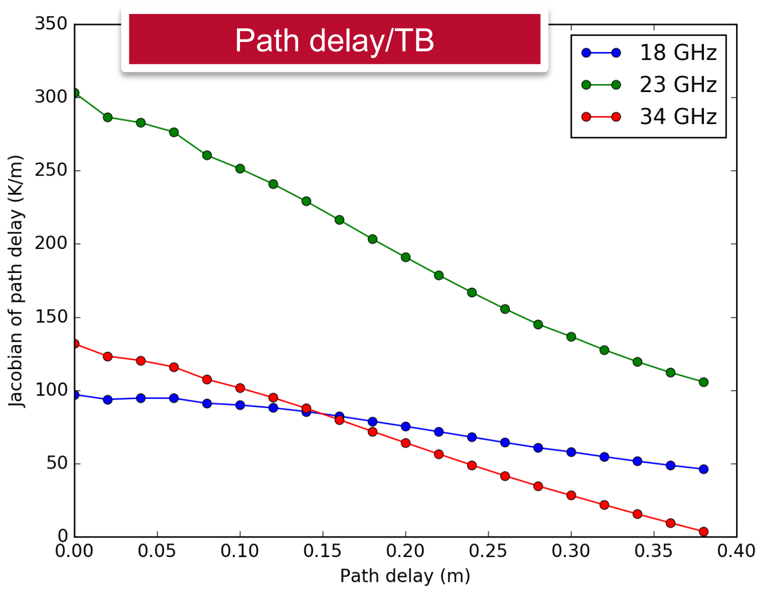
CAPRS: Passive Microwave Forward Model

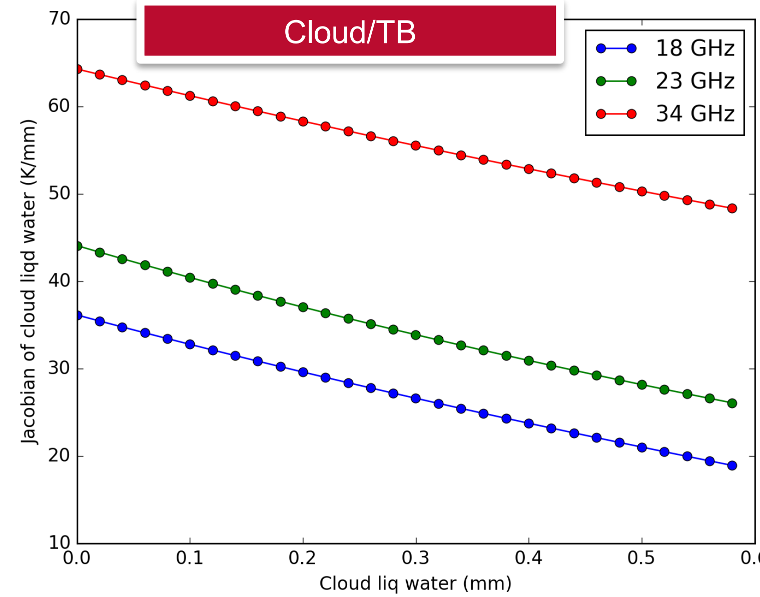
- Parameterized single layer radiative transfer model (Brown et al. 2006)
- Input:
  - Integrated water vapor/path delay (from state vector **x**)
  - Integrated cloud liquid water (from state vector **x**)
  - Wind speed (from state vector **x**)
  - Sea surface temperature (MERRA-2)
- Output:
  - TBs at 18.7, 23.8, 34.0 GHz frequencies

$$T_B = \varepsilon T_{sfc} e^{-\tau} + \left(1 - e^{-\tau}\right) T_{Eff}^{UP} + (1 - \varepsilon)\left(\left(1 - e^{-\tau}\right) T_{Eff}^{DOWN} + T_{\mathrm{cosmic}} e^{-\tau}\right) e^{-\tau}$$

$$emissivity = f(wind\ speed, sst)[FASTEM]$$

CAPRS: Jacobian Model and Sensitivity

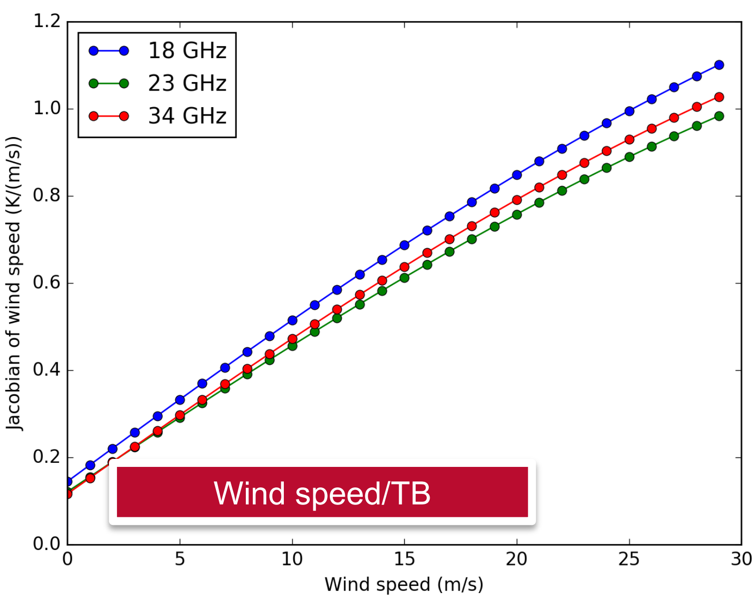


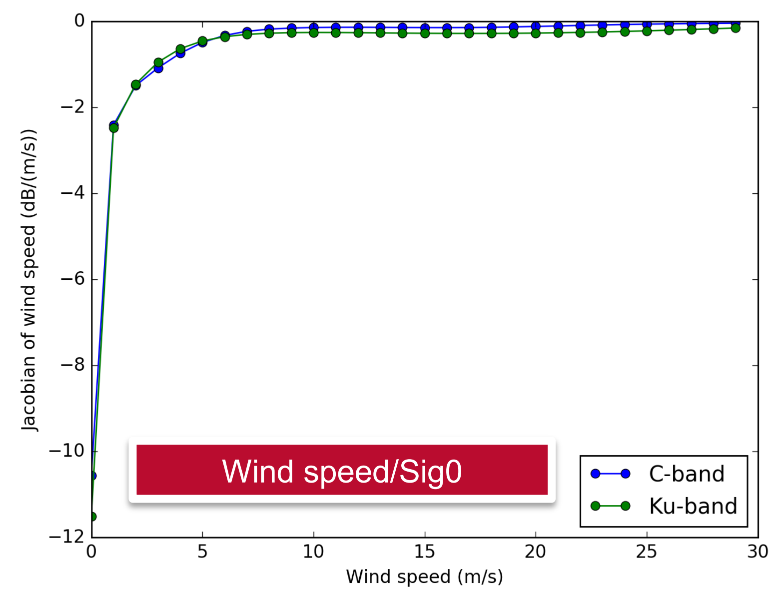


Jacobian Model

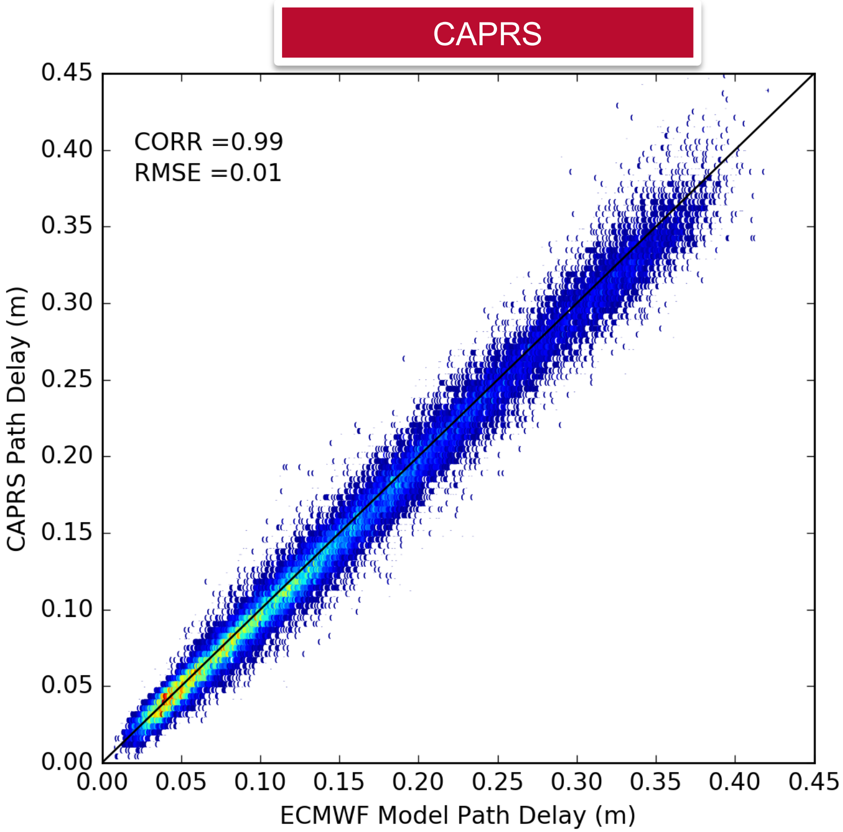
(Finite Difference)

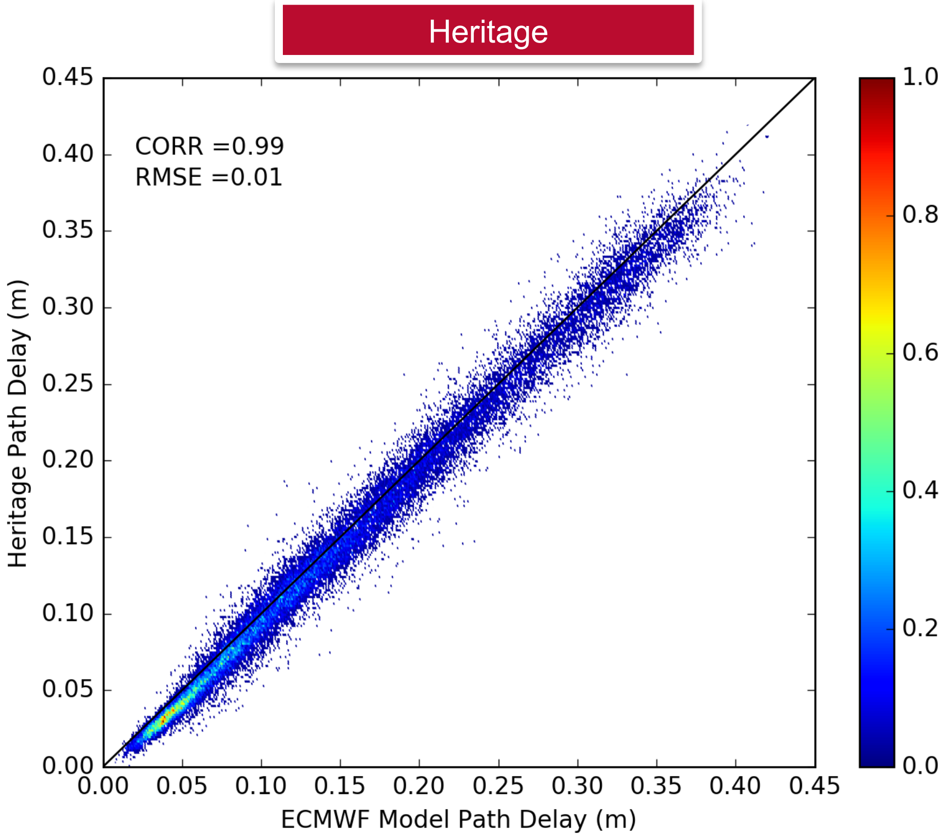
$$K = \frac{\delta y}{\delta x}$$





Performance Assessment: Path Delay

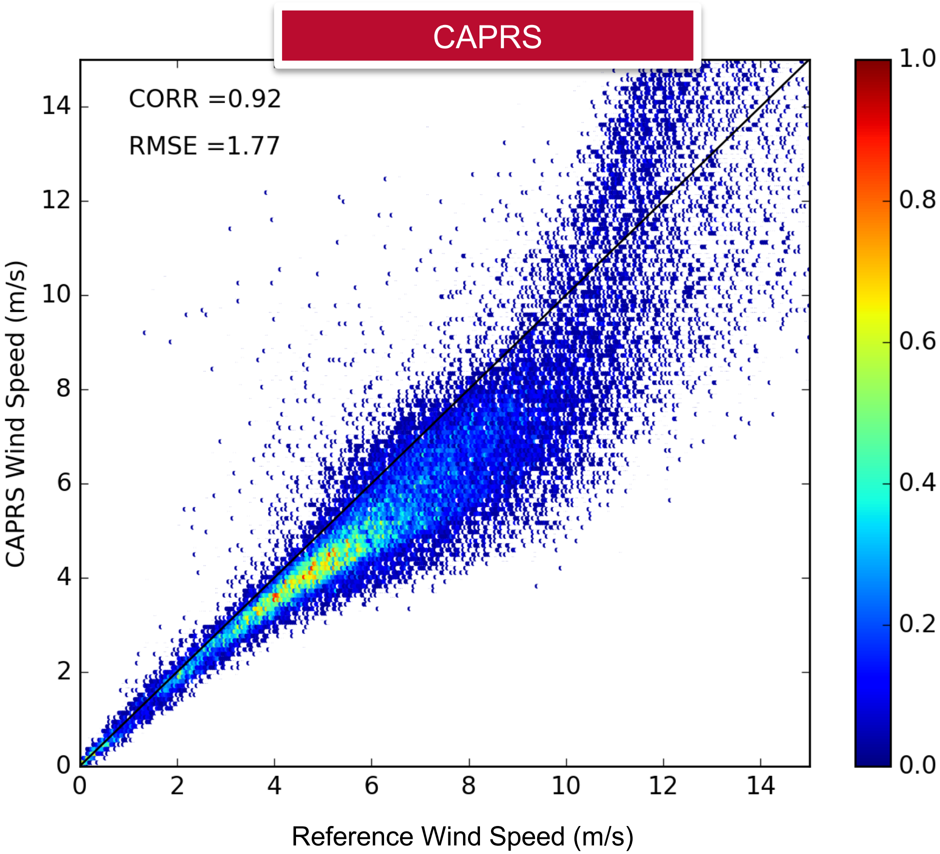


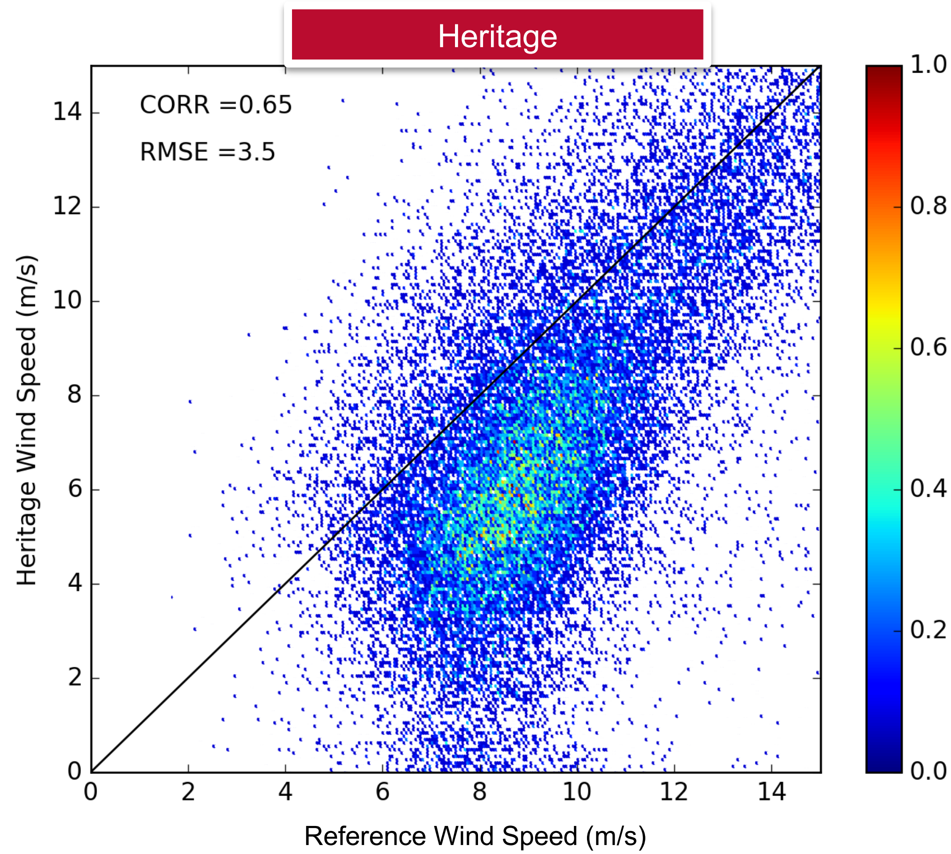


CAPRS Uncertainty: ~0.01 m

~ 4 months assessment period on Jason-3:
Apr 2017 –Aug 2017

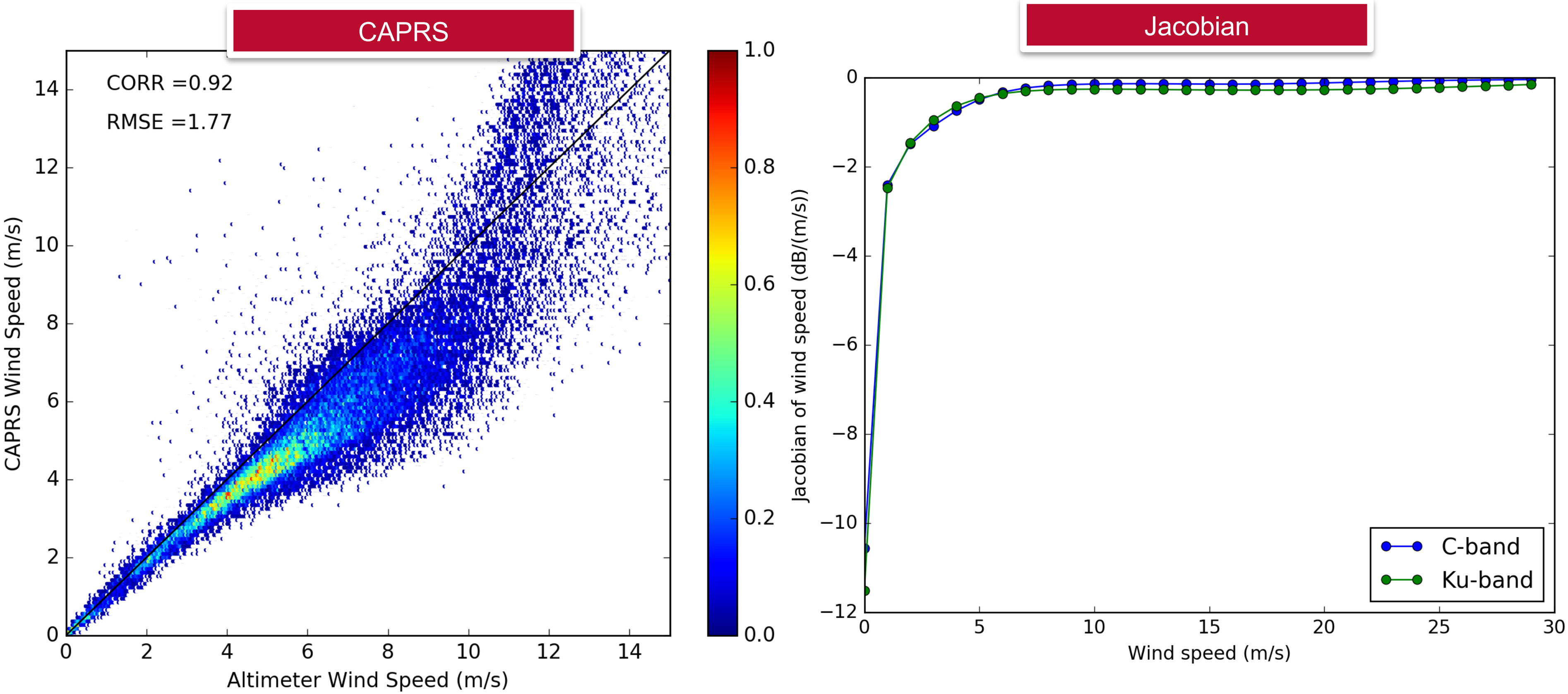
Performance Assessment: Wind speed





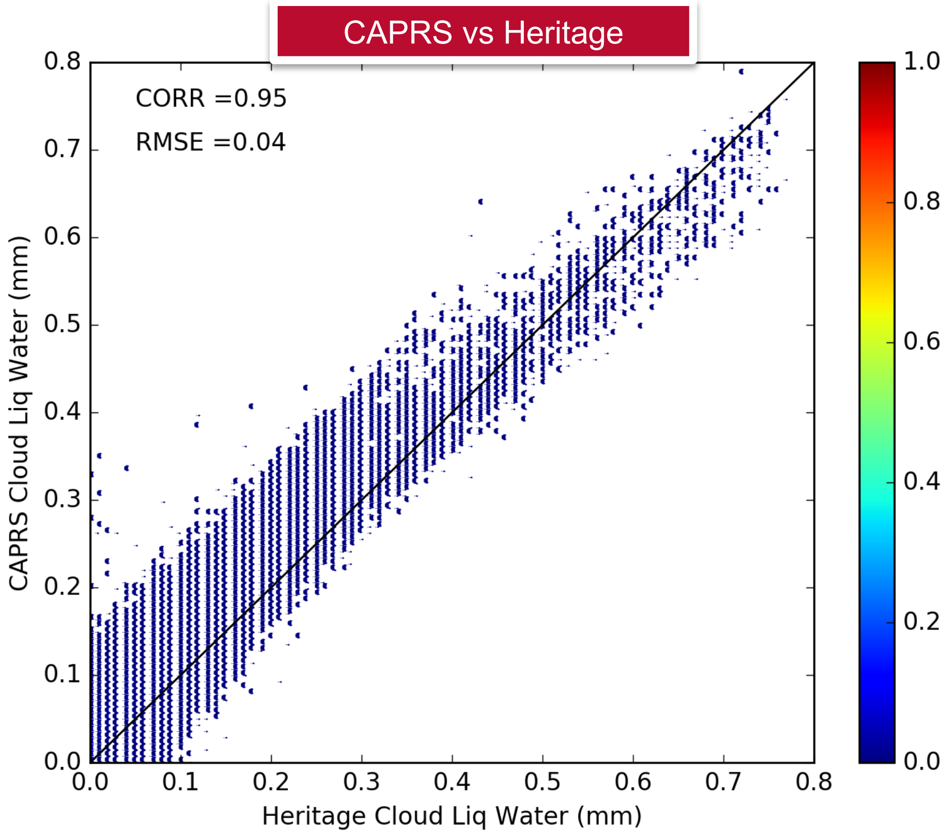
CAPRS Uncertainty: ~1.77 m/s

Performance Assessment: Wind Speed



Sensitivity reduces in high wind speed ranges (~>6 m/s)

Performance Assessment: Cloud Liquid Water



CAPRS Uncertainty: ~0.04 mm

Summary and Future Work

- Developed an active/passive retrieval algorithm that seamlessly integrates the radar and radiometer measurements to produce retrieval products of wet path delay and ocean wind speed.
- Algorithm still in development, but initial results promising.
- Algorithm benefit will be best revealed through reduction of regional systematic biases.
- Future work:
  - Improving retrieval performance
  - Development of value added products such as precipitation and cloud liquid water path
  - Extensive validation

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